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# Radio and $\gamma$-ray connection in relativistic jets

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Relativistic jets are one of the most powerful manifestations of the release of energy related to the supermassive black holes at the centre of active galactic nuclei (AGN). Their emission is observed across the entire electromagnetic spectrum, from the radio band to gamma rays. Despite decades of efforts, many aspects of the physics of relativistic jets remain elusive. In particular, the location and the mechanisms responsible for the high-energy emission and the connection of the variability at different wavelengths are among the greatest challenges in the study of AGN. Recent high resolution radio observations of flaring objects locate the high-energy emitting region downstream the jet at parsec scale distance from the central engine, posing questions on the nature of the seed photons upscattered to $\gamma$-rays. Furthermore, monitoring campaigns of the most active blazars indicate that not all the high energy flares have the same characteristics in the various energy bands, even from the same source, making the interpretation of the mechanism responsible for the high-energy emission not trivial. Although the variability of the most luminous blazars is well explained by the "shock-in-jet" scenario, the sub-class of TeV emitting objects suggests a more complex emission model with velocity gradients in a structured jet. This contribution presents results obtained by recent multiwavelength campaigns of blazars aimed at studying the radio and $\gamma$-ray connection and the physical mechanisms at the basis of the emission in these low and high energy bands.

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## 1. Introduction

The $\gamma$-ray sky is dominated by the population of active galactic nuclei (AGN). AGN are about 58% of the objects in the third *Fermi* Large Area Telescope source catalog (3FGL; Acero et al. 2015), which reports the $\gamma$-ray sources detected by *Fermi*-LAT in the first four years of scientific observations. A part from cosmic-ray related high energy emission from a handful of normal galaxies (e.g., Ackermann et al., 2012), almost all the extragalactic sources are associated with radio-loud AGN. In radio-loud AGN the radio emission is comparable or even stronger than the emission observed in the other energy bands, and is associated with the presence of a bipolar outflow of relativistic plasma that is responsible for both synchrotron (from radio up to X-rays) and inverse Compton radiation (at high energies).

The large majority ($\sim$98%) of the AGN emitting at high energies is represented by the blazar population which comprises flat spectrum radio quasars (FSRQ) and BL Lac objects. In these objects the relativistic jet is aligned to our line of sight and the emission is amplified by Doppler boosting effects. The remaining 2% are associated with misaligned AGN, as reported in the third catalog of AGN detected by *Fermi*-LAT (3LAC; Ackermann et al., 2015). It is worth noting that during the EGRET era, only three radio galaxies were proposed as the low-energy counterpart of $\gamma$-ray sources (Centaurus A, NGC 6251, J1737-15; Hartman et al., 1999), but Casandjian & Grenier (2008) did not confirm the association.

The dominance of the radio-loud population among $\gamma$-ray emitting objects have suggested a possible relation between the emission in radio and $\gamma$-ray energy bands. This connection is supported by the spectral energy distribution (SED) of the blazar sub-classes, which are well-modeled just by changing the radio luminosity. This suggests common under-lying physical processes linking the synchrotron and the inverse Compton emission (Fossati et al., 1998).

Although $\gamma$-ray-loud AGN are radio-loud sources, this does not imply that all the radio-loud AGN are $\gamma$-ray emitters. In particular, blazars with strong $\gamma$-ray emission are brighter and more luminous at radio frequencies (Kovalev et al., 2009), have faster jets (Lister et al., 2009) and higher variability Doppler factors (Savolainen et al., 2010) with respect to those without (significant) $\gamma$-ray emission, indicating that *Fermi*-LAT mainly detects the brightest objects from radio flux-density-limited samples.

Despite decades of efforts, many aspects of the physics of relativistic jets remain elusive. In particular, understanding how the jet is launched and accelerated, what is its structure, where is the high-energy emitting region and what is the responsible mechanism, are among the greatest challenges in the study of AGN. So far, many scenarios have been proposed for describing the typical variability observed in blazars. The "shock-in-jet" model predicts that a disturbance in the jet forms a shock that propagates downstream along the jet and is responsible for both the high and low energy emission (e.g., Marscher & Gear, 1985). On the other hand, the "structured-jet scenario" predicts that the jet has a velocity structure, and the high- and low-energy emission comes from different regions (e.g., Ghisellini et al., 2005).

Understanding what drives the emission at low and high energies will provide strong constraints on the open questions about the physics of the relativistic jets. By combining information arising from (high resolution) radio observations and $\gamma$-ray light curves it will be possible to investigate the presence of shocks, turbulence, or velocity gradients in the jet, the nature of the seed photons

upscattered at high energy, as well as the magnetic field structure.
This contribution reports on some recent results on the radio/$\gamma$-ray connection and on the physical mechanisms that may relate the emission in these two bands.

## 2. Radio/GeV connection

### 2.1 Statistical studies

Many statistical works have been carried out in order to confirm, or not, a radio/$\gamma$-rays connection. A detailed statistical analysis of the correlation between radio and $\gamma$-ray emission of AGN detected by *Fermi* during its first year of operation was presented in Ackermann et al. (2011). This work made use of the largest data set ever used so far. They found that the statistical significance of a positive correlation between the centimeter radio emission and the broadband (100 MeV $<$E $<$ 300 GeV) $\gamma$-ray energy flux is very high for the whole AGN sample, and increases when FSRQ and BL Lacs are considered separately. A similar result was suggested by Ghirlanda et al. (2010) who considered a much smaller sample. The radio-$\gamma$-ray correlation becomes very weak when energies E$>$10 GeV are considered, suggesting a physical rather than an observational origin for explaining such a lack of correlation (Giroletti et al., 2015).
The coexistence of *Fermi* and *Planck* satellites in orbit has enabled the exploration of the connection between the $\gamma$-rays and the radio emission at (sub-)millimeter wavelengths. In their work, Leon-Tavares et al. (2012) found a correlation between the $\gamma$-ray and (sub-)mm luminosity which holds over five orders of magnitude. However, in some bands the correlation becomes more significant when quasi-simultaneous observations (within 2 months) are considered. Observations of some time delay between the variability in the different energy bands have implication on the mechanism at the basis of the flare and its location. For this reason, important information on the physics of relativistic jets may be obtained by exploring the multi-band variability emission.

### 2.2 Radio/GeV correlated variability

Blazars show strong variability across the entire electromagnetic spectrum and a simultaneous or delayed occurrence may indicate the location of the variability region. Delayed variability at the long wavelengths is expected in presence of opacity effects from the innermost compact region of the AGN (within the broad line region, BLR). On the other hand, a rough simultaneity of radio and GeV flares locates the production of the $\gamma$-ray photons in a region downstream the jet, where the radio emission is not self-absorbed.
Because *Fermi* operates in an all-sky scanning mode, it is possible to compare the $\gamma$-ray light curves with radio light curves from dedicated monitoring programmes. Fuhrmann et al. (2014) presented results of a cross-correlation analysis between $\gamma$-rays and cm/mm wavelengths of a sub-sample of *Fermi*-bright blazars. They found a highly significant correlation between the two bands, with the radio lagging $\gamma$-rays. The time delay between high energies and radio is (7$\pm$9) days at 142 GHz and systematically increases as longer wavelengths are considered, becoming (76$\pm$23) days at 2 GHz. The frequency-dependent time lag is in agreement with the opacity of the jet. This suggests

that the $\gamma$-rays instantaneously escape from the production site, while the radio emission from the same region becomes optically thin progressively at later times, as a consequence of energy losses. The short time delay between $\gamma$-rays and (sub-)millimeter emission indicates that the $\gamma$-ray site is located about 1 pc upstream the mm core region.

A different conclusion was drawn by Leon-Tavares et al. (2011) who compared 37-GHz and $\gamma$-ray light curves. They noticed that statistically the rising of the mm light curve precedes the $\gamma$-ray peak of a few months (observer's frame), suggesting that the high energy flare takes place a few parsecs downstream along the jet. This opens questions on the seed photons which are upscattered to the high energies. In fact, at such a distance from the central region, the UV photons from the BLR are not effective anymore, and other seed photons, like the IR from the dusty torus (e.g. Sikora et al., 2008), or synchrotron photons from a different electron population must be considered. On the other hand, the strongest $\gamma$-ray flares occur during the rising/peaking stages of the mm light curve, suggesting that both episodes are related to the same disturbance.

## 3. The role of VLBI

The studies described in the previous Sections refer mainly to radio observations with single-dish telescopes. Low resolution observations cannot separate the contributions from the various source components. Observations with parsec-scale resolution are required to disentangle the flux density and the polarization of the core region from the emission arising from the jet and extended features.

Important information on the innermost region of relativistic jets comes from dedicated studies of bright blazars using the Very Long Baseline Interferometry (VLBI) technique. The (sub-)milliarcsecond-scale resolution of VLBI observations allowed a deep look into the jet base, revealing different structures, like the presence of superluminal knots (e.g., Jorstad et al., 2001a), changes in the jet direction, (e.g., OJ 287; Agudo et al., 2011), limb-brightened structures (e.g., M 87; Kovalev et al., 2007).

Monitoring campaigns of multi-frequency VLBI observations of $\gamma$-ray blazars detected by EGRET suggest that the highest level of $\gamma$-ray emission is connected to the ejection of a new superluminal component (e.g., Jorstad et al., 2001b). This supports the idea that at least the strongest $\gamma$-ray emission is strictly related to a shock in the jet.

### 3.1 Shock-in-jet model

In the shock-in-jet model, the flare originates as a disturbance that modifies the flow parameters and produces a shock wave (Marscher & Gear, 1985; Valtaoja et al., 1992). The shock model implies: (1) a growth stage, when the shock forms up to the development of its maximum, which is observed not simultaneously at the various energy bands due to opacity effects (Compton losses dominate); (2) a plateau, when energy losses and gains are balanced (synchrotron losses dominate); (3) a decaying stage, when the shock fades due to energy losses (adiabatic losses dominate).

The propagation of a transverse shock produces the amplification of the perpendicular component of the magnetic field with respect to the parallel one, and an enhancement of the luminosity.

However, if the shock is oblique the polarization properties may be different, depending on the obliqueness of the shock itself and to the characteristics of the underlying magnetic field like its order and strength (Hughes et al., 2011). It is worth noting that 90° rotation of the electric vector position angle (EVPA) are expected during the transition between the opacity regimes. However, such changes in the opacity would cause a dramatic drop of the flux density which is not observed. The shock-in-jet scenario naturally explains the frequency-dependent variability observed in many blazars, the detection of superluminal components that are interpreted as the observable manifestation of the propagating shock, and the abrupt rotation of 90° of the EVPA (e.g., Orienti et al., 2013a, 2011; Hovatta et al., 2008). Outstanding examples are the FSRQ 3C 454.3 and PKS 1510-089. These objects underwent major flares in $\gamma$-rays, reaching an apparent peak luminosity $\sim 10^{49-50}$ erg $s^{-1}$ (Orienti et al., 2013a; Abdo et al., 2011). The huge flares occurred near the peak of the millimeter flare and were accompanied by the emergence of a superluminal knot with apparent speed above 10-20*c*, indicating a tight connection between $\gamma$-ray flares and changes in the parsec-scale jet structure (Jorstad et al., 2013; Orienti et al., 2013a). However, the location of the $\gamma$-ray production region is not unambiguously determined. The short time lag derived between the $\gamma$-ray flare and the detection of both a new component and the mm flare indicates that the high energy region is located in the millimeter photosphere, i.e. the region where the mm emission becomes optically thin, a few parsecs away from the BLR.

In OJ 287 Agudo et al. (2011) reported that $\gamma$-ray peaks are likely associated with a large increase of the linear polarization from a jet component located about 14 parsec from the central engine, strongly indicating that the dissipation region is located well downstream along the jet as a consequence of the interaction between a disturbance and a standing conical shock. If we consider that the entire cross-section of the jet is responsible for the $\gamma$-ray emission, this scenario is rather difficult to reconcile with the size expected on the basis of the causality argument, unless the collimation angle of the jet is extremely small, or the flaring region occupies only a fraction of the jet cross section. The latter scenario is supported by the observations of frequent changes and large jumps in the position angle of the direction of the superluminal knots moving along the jet (Lister et al., 2013).

In PKS 1510-089 no correlation between the jet properties and the $\gamma$-ray flares was found, indicating that the high-energy emission does not arise from the knot itself, but it is likely located in the unresolved core component. By following the evolution of three superluminal knots in PKS 1510-089, Orienti et al. (2013b) found that the flux density decreases with time as expected for adiabatic losses, and the polarization percentage increases reaching values up to 10%, much larger than what is found in the core component. Remarkably, all the knots are characterized by the same EVPA $\sim$80°, once they emerge from the core.

Not all the $\gamma$-ray flares have a clear counterpart at low energies even if they are produced by the same source, like in the case of some outbursts of 3C 279 and BL Lac where no significant radio variability was detected after the $\gamma$-ray flare (Abdo et al., 2010; Marscher et al., 2008). In this case the trigger should be a disturbance that develops in the innermost region of the AGN, within the BLR, where the emission is utterly opaque at the radio wavelengths.

It is worth mentioning that not all the radio flares and the ejection of new superluminal components are associated with high energy flares. Straightforward examples are the Narrow Line Seyfert 1 SBS 0846+513 and the FSRQ 4C 49.22 where the radio peak and the ejection of a new component

are not related to any obvious high energy activity (D'Ammando et al., 2013; Cutini et al., 2014). The lack of a high energy counterpart may be related to the absence of enough seed photons in the region where the energy dissipation takes place. On the other hand, in these objects high $\gamma$-ray activities occur during low radio activity states, suggesting different regions and/or mechanisms for low and high energy variability.

### 3.2 The Structured-jet model

Although it proved to be successful in describing many aspects of the most luminous blazars, the shock-in-jet model seems inadequate for reproducing the observational properties and the spectral energy distribution of TeV blazars and radio galaxies. Although the high energy emission implies high Doppler factors and extreme bulk motion VLBI observations of TeV objects did not reveal any superluminal jet component.

The properties of TeV objects are better explained by the structured-jet scenario, which postulates a velocity gradient in the jet, either transverse (faster central spine surrounded by a slower layer; e.g. Ghisellini et al. 2005) or radial (the flow decelerates as it moves outward; e.g. Georganopoulos & Kazanas 2003). The spine-layer model is supported by observations in TeV objects of limb-brightened structure both in total intensity (e.g., the BL Lac Mrk 501 and the radio galaxy M87; Giroletti et al. 2008, Kovalev et al. 2007) and in polarized emission (e.g., the BL Lac Mrk 421; Lico et al., 2014). In this scenario the electrons of each region upscatter the beamed soft photons coming from the other.

The lack of a unique zone responsible for high and low energy emission may produce a large variety of correlation, as well as uncorrelated variability. This seems the case of the radio galaxy 3C 84 at the centre of Perseus cluster. The $\gamma$-ray and radio light curves of 3C 84 do not seem correlated, and no obvious radio flare is associated with the episodes of Very High Energy (VHE, E$>$100 GeV) emission (Nagai et al., 2012). Interestingly, this source was not detected in $\gamma$-rays by EGRET. After three months of scientific observations, *Fermi*-LAT detected $\gamma$-ray emission from 3C 84 at a level 7 times higher than the EGRET upper limit, indicating that the lack of $\gamma$-ray emission during the EGRET era was intrinsic to the source rather than due to sensitivity limitation (Abdo et al., 2009). A change in the physical characteristics of 3C 84 is marked by the different structure of the jet: edge-darkened in the EGRET era, and limb-brightened in the *Fermi* era (Nagai et al., 2014). This poses strong evidence in favour of the jet-structured scenario for this misaligned AGN.

## 4. Concluding remarks

Multiwavelength monitoring campaigns suggest a relation between $\gamma$-ray flares and the radio variability. However, the time delay is different if the peak or the rising of the mm outburst are considered. In the former case the $\gamma$-ray peak precedes the radio one with a time lag increasing as longer wavelengths are considered. On the other hand, in case of strong $\gamma$-ray flares, the $\gamma$-ray flare seems to follow the onset of the radio outburst suggesting that the dissipation region occurs at parsec-scale distance from the central engine. The observed variability is usually explained in terms of a shock moving along the jet, whose manifestation is a superluminal knot observable with

high-frequency VLBI observations. However, the variability observed in $\gamma$-rays does not always show the same properties in the other energy bands, and it is possible that different $\gamma$-ray flares of the same source originate at different distances from the central engine.
The "shock-in-jet" model is not able to reproduce the observational properties of low-luminosity blazars. For example, the $\gamma$-ray properties of the TeV emitting blazars and radio galaxies are better explained by a two-zone model that assumes a gradient velocity in the jet, either radial or transverse. This "structured-jet scenario" is supported by observations of limb-brightened structures of the jet, likely witnessing a faster central spine surrounded by a slower layer. Therefore, low and high energy emission originates in different regions and a connection between the radio and $\gamma$-rays may not be trivial.
The advent of the Cherenkov Telescope Array, operating in the GeV/TeV band, will allow us to investigate the physics of relativistic jets in the most extreme objects which are not well sampled by the *Fermi*-LAT energy bands.

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